Multi-sensor Improved Sea Surface Temperature (MISST) for GODAE

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LONG-TERM GOALS

The Multi-sensor Improved Sea Surface Temperatures (MISST) for the Global Ocean Data Assimilation Experiment (GODAE) project intends to produce an improved, high-resolution, global, near-real-time (NRT), sea surface temperature analysis through the combination of satellite observations from complementary infrared (IR) and microwave (MW) sensors and to then demonstrate the impact of these improved sea surface temperatures (SSTs) on operational ocean models, numerical weather prediction (NWP), and tropical cyclone intensity forecasting. SST is one of the most important variables related to the global ocean-atmosphere system. It is a key indicator for climate change and is widely applied to studies of upper ocean processes, to air-sea heat exchange, and as a boundary condition for numerical weather prediction. The importance of SST to accurate weather forecasting of both severe events and daily weather has been increasingly recognized over the past several years. Despite the importance and wide usage of operational SST analyses, significant weaknesses remain in the existing operational products.

The improved sensors on the Terra, Aqua, and EnviSAT-1 satellites, in conjunction with previously existing sensors on several other US Navy, NASA, and NOAA satellites, provide the opportunity for notable advances in SST measurement. In addition to more frequent coverage for increased temporal resolution, these sensors permit the combination of highly complementary IR and MW retrievals. Characteristically, IR SST provides high spatial resolution (~1 km) but poorer coverage with the presence of clouds. Although having a reduced resolution (~25 km), MW SST provide >90% coverage of the global ocean each day. These factors have motivated interest in the development of merged IR and MW SST products to leverage the positive characteristics of each sensor type. Merging multiple

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SST sensors into a single analysis will result in enhanced operational reliability, data availability, and analysis accuracy.

This project has two distinct goals: (1) producing an improved sea surface temperature (SST) product through the combination of observations from complementary IR and MW sensors, and (2) demonstrating the impact of improved multi-sensor SST products on operational ocean models, numerical weather prediction, and tropical cyclone intensity forecasting. Close collaboration and the international coordinated exchange of SST products with error statistics with operational agencies will optimize utility of these new data streams by US and international operational agencies. Innovative techniques to blend these complementary data will be applied in operational frameworks at NOAA and Navy. This project will make a direct US contribution to GODAE by working within the GODAE High-Resolution SST Pilot Project (GHRSST-PP), initiated by the international GODAE steering team, to coordinate the production of a new generation high-resolution SST. By contributing to the GHRSST-PP this team will minimize duplication of efforts, harmonize research and development activities, and maximize data access.

This effort will ensure that US scientists and operational activities remain at the forefront of the international ocean and weather forecasting activities and are provided with state-of-the-art SST data products and analyses.

OBJECTIVES

To produce multi-sensor improved SSTs and successfully assess the impact of these products, five clear project objectives have been identified: 1) Computation of sensor-specific observational error characteristics. 2) Parameterization of IR and MW retrieval differences, with consideration of diurnal warming of the ocean surface and cool-skin effects at the air-sea interface. 3) Production and dissemination of Level 2 Processed (L2P) sensor-specific SST products. 4) Production of improved multi-sensor high-resolution SST analyses. 5) Targeted impact assessment of the new SST analyses.

APPROACH

Production of a multi-sensor, improved SST product requires detailed, consistent processing of all input data and characterization of retrieval errors and differences in addition to development of fusion techniques. Much of the methodology to be applied is selected for consistency with the GHRSST-PP Data processing Specifications (GDS), which is designed to produce SST data products that satisfy the requirements of existing operational ocean forecast and prediction systems. This project will also provide an assessment of the operational impact of improvements by the enhanced sampling and error characterization of the IR and MW sensors in the areas of NWP and ocean modeling. Targeted applications include Navy fleet operations, naval and civilian NWP, operational oceanography, and climate monitoring and forecasting. Each of these areas is of national importance and has corresponding national programs. For each of these applications, it is anticipated that this project will provide significant enhancements to the quality and availability of data. Through affiliation with the GHRSST-PP, the products will also be directly utilized by the international GODAE modeling communities. This product sharing will be achieved through the partnerships and close connections between the data provider and user communities.

The MISST project has a broad partnership of scientists from academia, government, and private industry, including Remote Sensing Systems, NOAA (NESDIS, NCDC, NODC, ESRL), US Navy (NRL, NAVOCEANO), NASA (JPL PODAAC), U. Maryland, U. Edinburgh, U. Miami, Florida State U., U. Colorado, Old Dominion U., and the International GHRSST-PP Project Office. The project has identified specific tasks: data provision (C. Gentemann, B. Evans, D. May, E. Maturi), determining sensor errors (G. Wick, C. Gentemann, A. Harris, P. Minnett, B. Evans, S. Castro, B. Emery, D. May), modeling diurnal warming and skin layer effects (G. Wick, C. Gentemann, S. Castro, B. Emery, B. Ward), production and distribution of data analyses (J. Cummings, E. Maturi, J. Vasquez), and performing impact studies (M. Ji, J. Cione, J. Goerss, N. Baker, E. Chassignet, C. Barron).

WORK COMPLETED

(1) Produced GHRSST-PP compliant L2P formatted data for GOES-E, GOES-W, MODIS-Terra, MODIS-Aqua, gridded TMI, and gridded AMSR-E SSTs (2) continued the NRT *in situ* satellite database, (3) determined SSES for GOES-E, GOES-W, MODIS-Terra, and MODIS-Aqua, (4) updated SSES for AVHRR, TMI, and AMSR-E, (5) continued production of L2P SSTs AVHRR, TMI, and AMSR-E, (6) updated diurnal and skin layer modules, (7) continued development on blended SSTs, and (8) performed impact studies.

RESULTS

(1) Produced GHRSST-PP compliant L2P formatted data for GOES-E, GOES-W, MODIS-Terra,MODIS-Aqua SSTs, gridded TMI, and gridded AMSR-E . GHRSST compliant L2P SSTs are now being produced by the NOAA Office of Satellite Data Processing and Distribution (OSDPD) operational environment for GOES-E and GOES-W. NASA's Ocean Biology Processing Group (OBPG) now produces L2P SSTs for MODIS TERRA and AQUA. RSS now produces gridded TMI and gridded AMSR-E L2P SSTs in GHRSST compliant L2P data format. MODIS, TMI, and AMSR-E L2P data are available for both NRT and archive (from launch).

(2) Continued the NRT in situ satellite database. Database updated continually with AVHRR by NAVOCEANO, with TMI and AMSR-E by RSS, and with GOES-E, GOES-W, MT-SAT, and MSG by NOAA. The database is updated monthly for MODIS TERRA and AQUA by U. Miami.

(3) Determined SSES for GOES-E, GOES-W, MT-SAT, MSG, MODIS-Terra, and MODIS-Aqua. GOES SSES are determined using clear-sky transmittance calculated from radiative transfer modeling and NCEP air-sea temperature differences. NOAA is in the process of characterizing errors for MT-SAT and MSG in order to develop a NOAA L2P operational product for these sensors. A complete set of SSES, the MODIS uncertainty hypercubes for mean and standard deviation, have been generated for TERRA and AQUA using all available *in situ*-satellite matchup points from launch through mid-2007.

(4) Updated SSES for AVHRR, TMI, and AMSR-E. Error characteristics for AVHRR are continually updated by NAVOCEANO. NOAA and the University of Colorado have extended the derivation of alternative environmentally-based SSES for AVHRR to include the sensor on the NOAA-18 satellite. The study specifically evaluated the retrieval bias as a function of SST to fulfill a request from the Navy to understand the sources of the SST bias at cold temperatures in the NAVO retrieval algorithm. Error characteristics for TMI and AMSR-E are continually updated. Static error tables for TMI and AMSR-E were updated after the September 2006 TMI and AMSR-E reprocessing.

(5) Continued production of GHRSST-PP compliant L2P formatted data for AVHRR, TMI, and AMSR-E. NAVOCEANO has continued producing NRT AVHRR L2P. RSS has continued producing orbital NRT TMI and AMSR-E L2P. All data was reprocessed after the algorithm updates to TMI and AMSR-E in September 2007. All MISST datasets are provided to the NASA JPL Global Data Assembly center for NRT distribution and are automatically archived at the NOAA NODC GHRSST Long Term Stewardship and Reanalysis Facility (LTSRF, http://ghrsst.nodc.noaa.gov).

(6) Updated diurnal and skin layer modules. An improved physics-based diurnal warming model, the Profiles of Ocean Heating (POSH) model, has been developed specifically for application within this project (Fig. 1). Validation of a detailed second moment turbulence closure model for diurnal warming was extended with new skin layer observations and characteristic temperature profiles were generated from idealized forcing for incorporation in the simplified diurnal warming model (Fig. 2).

(7) Continued development on blended SSTs. The MISST project has several blended SST analyses. The research analysis is developed at RSS while operational analyses are being developed within NOAA and US Navy. This project is focused on the transition of research to operations. Development of blended SSTs requires new data streams. NAVOCEANO has improved on its methodology to add retrieval error information to the US Navy operational data stream. Quantitative estimates of reliability are added to each MCSST sample utilized at NAVOCEANO. Retrieval errors are calculated for N-17, N-18, and METOP-A GAC, N-17 and N-18 LAC, AATSR, MSG, and orbital AMSR-E data. NOAA has extended coverage of SST retrieval from geostationary satellites to include MT-SAT and Meteosat-9 (Fig. 3). Both sensors have some calibration issues which will be addressed in the final SST product. NOAA is producing a new daily blended POES/GOES analysis. The POES-GOES analysis software has been transferred to the NOAA OSDPD operational environment. RSS is producing a blended daily 9 km global SST analysis using MODIS, TMI, and AMSR-E data (Fig. 4). This analysis includes corrections for diurnal warming.

(8) Performed impact studies. NRL evaluated the impact of MISST SSTs on Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Navy Coupled Ocean Data Assimilation (NCODA) system. It was found the MISST SSTs did not degrade the persistence forecast skill of the NOGAPS operational analysis. Background error variances decreased in regions with persistent cloud cover, but increased at high latitudes in the southern hemisphere. The impact of MISST SSTs on NOGAPS tropical cycle (TC) track forecast errors and extra-tropical forecast performance was evaluated. No significant differences in the overall TC track forecast errors were found. However, there were areas where the blended SST analysis resulted in significantly improved TC track forecasts. Fig. 5 shows the two forecasts made at 00Z 22 September 2005 for Hurricane Rita. The blended SST forecast track was more in line with the actual track of the storm and the location and timing of landfall for Hurricane Rita was better predicted. No statistically significant difference in extra-tropical forecast performance for NOGAPS was found.

NRL globally evaluated the existing operational MODAS AVHRR-only SST and RSS MW SST. Overall performance of global SSTs from individual sensors and blended products showed error levels similar to the observational uncertainty. Transition to a blended SST would not be expected to have a large impact globally; however, in regions with persistent cloud cover the RSS MW SST gave superior correlations. Demonstration of positive improvement in some regions with no significant overall negative impact has led to a plan to transition a blended NCODA SST into Navy operational ocean products in 2008.

NOAA evaluated the impact of blended MW SSTs on the Statistical Hurricane Intensity Prediction System (SHIPS). Results from the SHIPS evaluation shows that the MW SST product reduced the intensity forecast error by about 2% for the Atlantic forecasts, with small positive to neutral impact for the eastern Pacific sample (Fig. 6). These results indicate that there is the potential to improve operational hurricane intensity forecasts by improving the SST analysis through the inclusion of MW data. SSTs during a hurricane are shown in Fig. 7.

IMPACT/APPLICATIONS

National Security: SST is routinely used both directly in Naval fleet operations and as an input to weather forecast models used to support Naval operations. The improved SST products and better understanding of the associated errors resulting from this project will provide a more accurate description of environmental conditions enabling better planning of operations. A key aspect of this project is directly evaluating the impact of the improved SSTs on Naval applications. SSTs are also a key parameter for identifying the location and strengths of thermal fronts and eddies, information crucial to assessing the acoustic environment for submarine and antisubmarine operations, as well as for Homeland Security considerations of coastal currents and eddies for public health and safety in the advent of deliberate dumping and dispersion of hazardous material.

Economic Development: SST data is a significant consideration for planning and conducting commercial fishing operations, as well as fisheries management and monitoring efforts. Likewise, SST data is relevant to marine protected species monitoring and de-conflicting protection efforts from commercial fishing.

Quality of Life: The potential for producing more accurate SST products has important application to areas including environmental monitoring and weather forecasting. More accurate knowledge of the SST can lead to improved understanding of coral health, better forecasting of routine and severe weather events, improved recreational fishing, and increased ability to monitor climate change. Improved understanding in these areas will lead to a more informed public and better decision-making. The specific focus on tropical cyclone intensity forecasting will potentially impact warning and evacuation decisions.

Science Education and Communication: The NASA Earth Observatory (EO) provides an online magazine includes feature articles, daily news and images, breaking news Earth Sciences events (www.earthobservatory.nasa.gov). MISST SSTs provide visuals for a variety of media updates, alerts (the most common of which are hurricane-related), and a number of museum projects. These data are quite useful for periodic requests from NASA/GSFC Public Affairs Office, staff scientists wanting to talk about events with reporters, etc. The MISST SSTs has also been appearing in flagship NASA productions, (eg: Hurricane Watch (www.nasa.gov/mission_pages/hurricanes/main/index.html), of which one of the most intriguing visualizations uses MISST SSTs, GOES clouds, and recorded storm tracks to show the 2005 hurricane season: (http://learners.gsfc.nasa.gov/mediaviewer/27storms/).

TRANSITIONS

National Security: Through direct project partnership with US Navy efforts, the improved SST products and methodologies will be directly integrated into Naval SST products and numerical weather forecasting procedures both in use and under evaluation. As one example, in FYO8 the NRL will

begin transition of the Navy Coupled Ocean Data Assimilation (NCODA) global SST into the operational data stream at NAVOCEANO for use in operational models. MISST contributed to the development of the NCODA SST, which blends IR and MW SSTs with *in situ* observations. The NCODA SST will replace the existing MODAS SST which utilizes only IR AVHRR observations from polar orbiters. To accomplish the goal of determining the impact of the SST improvements in Naval applications, transitioning results to the Naval partners is a central focus of this project.

Economic Development: Satellite IR SST data are already in use by the National Marine Fisheries Service. Improved coverage in persistently cloudy regions will facilitate protected species and fisheries management efforts. The merged IR-MW SST product will be provided when available via the NOAA CoastWatch program.

Quality of Life: Key impact assessments are planned in the areas of numerical weather prediction and tropical cyclone intensity forecasting through the activities of project partners. New SST retrievals and improved error estimates are to be integrated into existing forecast models to determine their impact. Additionally, the merged products will be provided to NOAA's National Weather Service (NWS) National Centers for Environmental Prediction (NCEP)'s Ocean Prediction Center to support ocean forecasting of winds and waves, as well as thermal conditions. Through involvement with the international GHRSST-PP, the resulting products will be further available for incorporation by a diverse, interested user group.

RELATED PROJECTS

"U.S. GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model (HYCOM)": http://hycom.rsmas.miami.edu/

"POSITIV: Prototype Operational System – ISAR – Temperature Instrumentation for the VOS fleet"
CIRA/CSU Joint Hurricane Testbed project (http://www.nhc.noaa.gov/jht/05-07_proj.shtml)
NRL Ocean Data Assimilation (ODA) project funded under PMW 180
NRL Improved Synthetic Ocean Profiles (ISOP) project funded under ONR

PUBLICATIONS

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HONORS/AWARDS/PRIZES

Dr. Charlie Barron, Naval Research Laboratory, 2006 Top Navy Scientists and Engineers of the Year Award, US Navy.

Dr. Chelle L. Gentemann, Remote Sensing Systems, 2007 Joint Assembly outstanding student presentation award, AGU.

Dr. Chelle L. Gentemann, Remote Sensing Systems, 2006 Joint Assembly outstanding student paper award, AGU.

Dr. Chelle L. Gentemann, Remote Sensing Systems, 2006 IEEE international geoscience and remote sensing symposium and 27th Canadian symposium on remote sensing student paper competition finalist, IEEE.

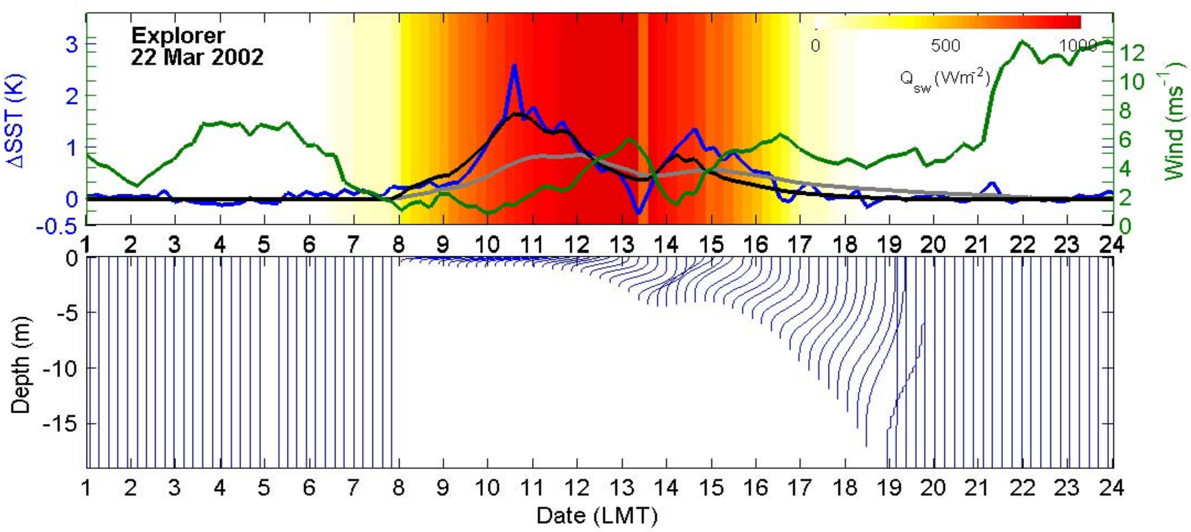

Figure 1. The top panel shows data from the Explorer of the Seas cruise ship. Insolation is shown in the background, wind speed (green line), diurnal warming measured by a skin radiometer (blue line), Fairall model (grey line), and POSH model (black line). In the bottom panel, normalized, scaled, profiles of the temperature within the diurnal thermocline, calculated by the POSH model are shown. Once a diurnal thermocline forms, the temperature profiles in the figures end at the base of the warm layer. On this day, there were two peaks in diurnal warming, directly related to two decreases in wind speed. The Fairall model amplitudes were too low and temporally lag the observed peaks for both occurrences. Both peaks were well defined in the POSH simulation and the maximums in warming were close to the observed maximums.

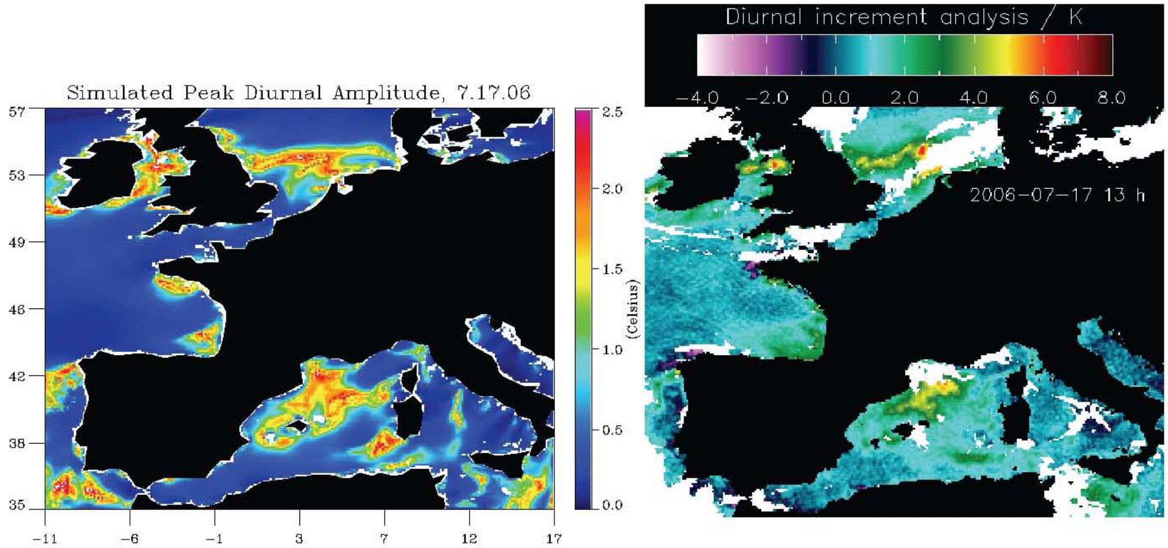

Figure 2. Regional application using modeled forcing data. Represented in the left panel are simulated peak diurnal amplitudes for one day using a modified Kantha/Clayson diurnal model in conjunction with a new turbulence scheme that incorporates additional turbulence generation near the surface from wave breaking. Peak diurnal amplitudes were computed with respect to the foundation temperature. The model was forced with solar fluxes from SEVIRI and turbulent fluxes from ECMWF modeled outputs. The right panel represents the corresponding observed diurnal warming from SEVERI data.

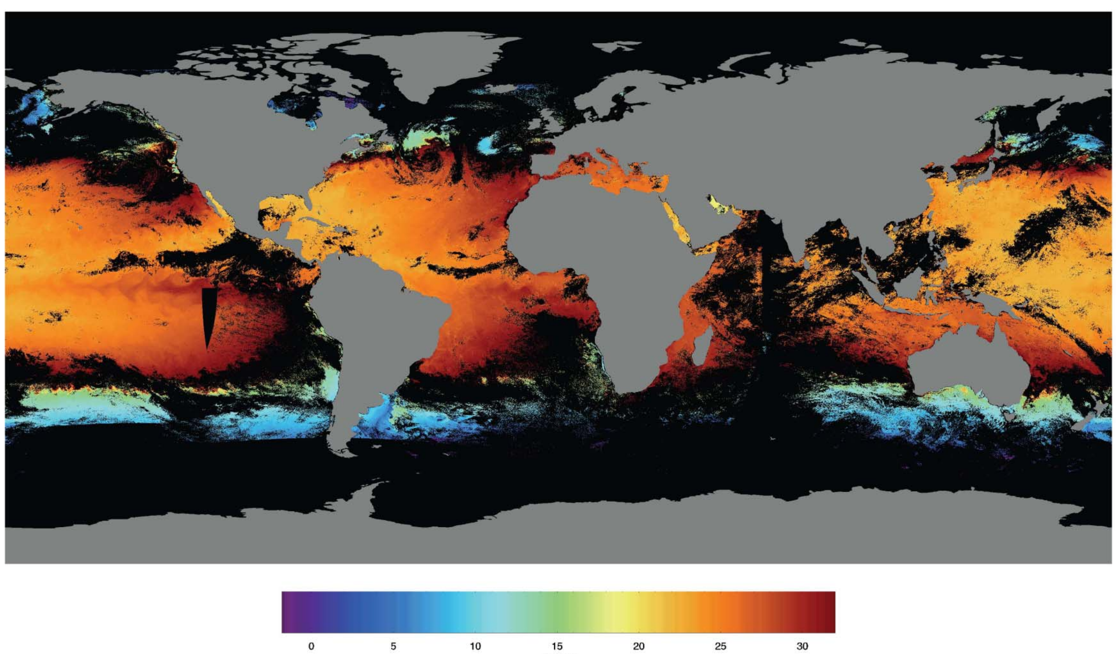

Figure 3. Composite NOAA SST retrievals for one day using (from West-to-East) GOES-11, GOES-12, Meteosat-9 and MT-SAT. The small triangular gap in the S Pacific is due to the GOES-11 and GOES-12 S Hemisphere scan sectors not overlapping completely. The gap in coverage in the Indian Ocean is a result of that region being beyond the limit of reasonable accuracy for Meteosat-9 (0°) and MT-SAT (140°E).

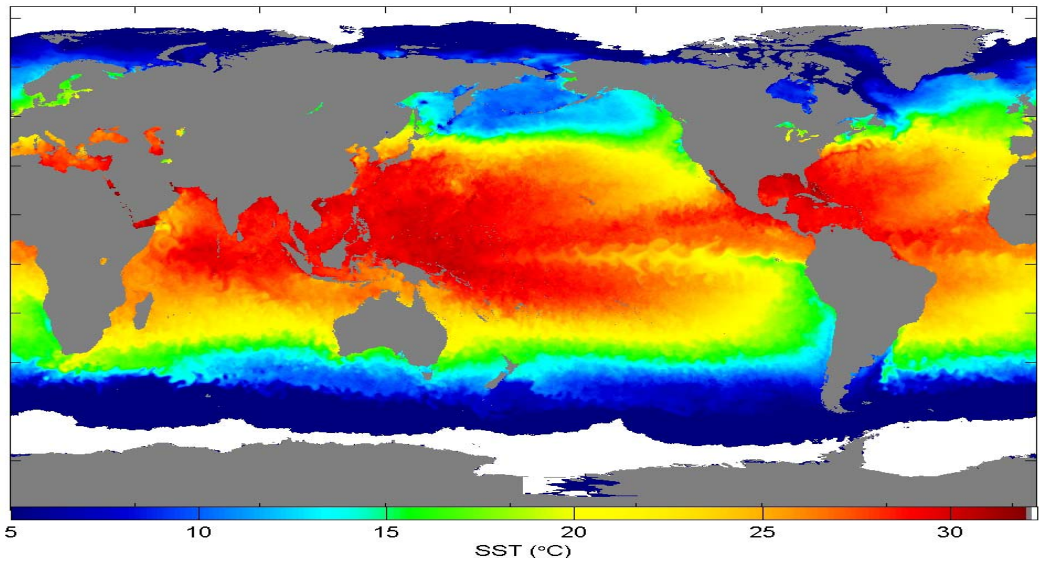

Figure 4. Global 9km MODIS, TMI, and AMSR-E blended SST on 1 September 2007.

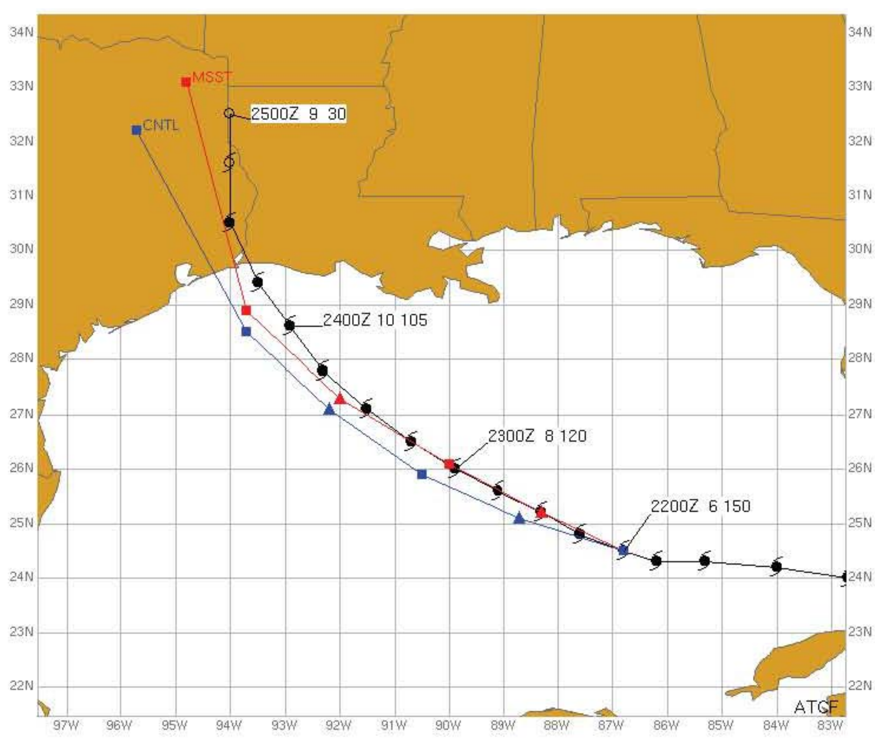

Figure 5. A comparison of the MISST blended SST (red) and operational SST (blue) NOGAPS track forecasts for Hurricane Rita, 00Z 22 September 2005. The black line and symbols denotes the actual storm track.

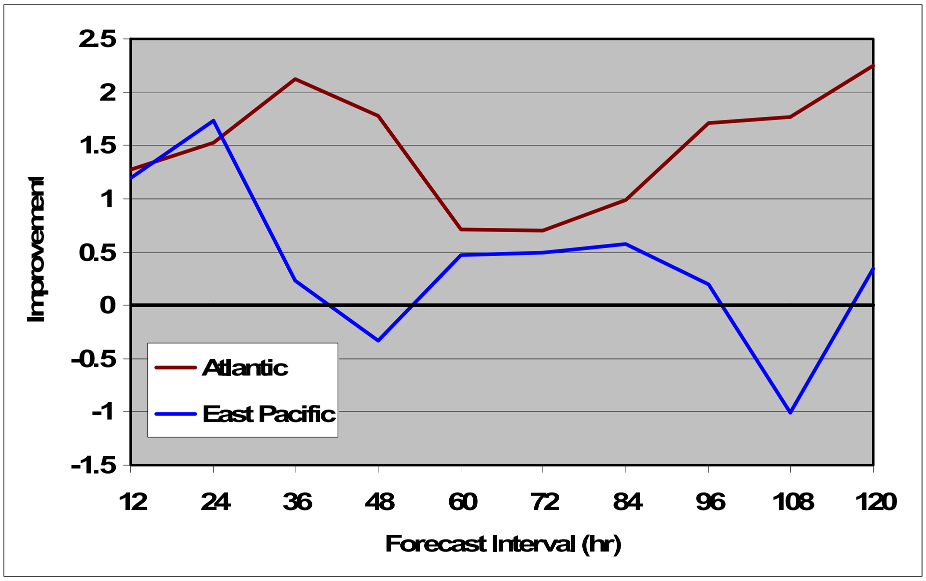

Figure 6. Improvement in the SHIPS intensity model due to the inclusion of MW SSTs for a large sample of forecast re-runs from the 2004-2006 hurricane seasons.

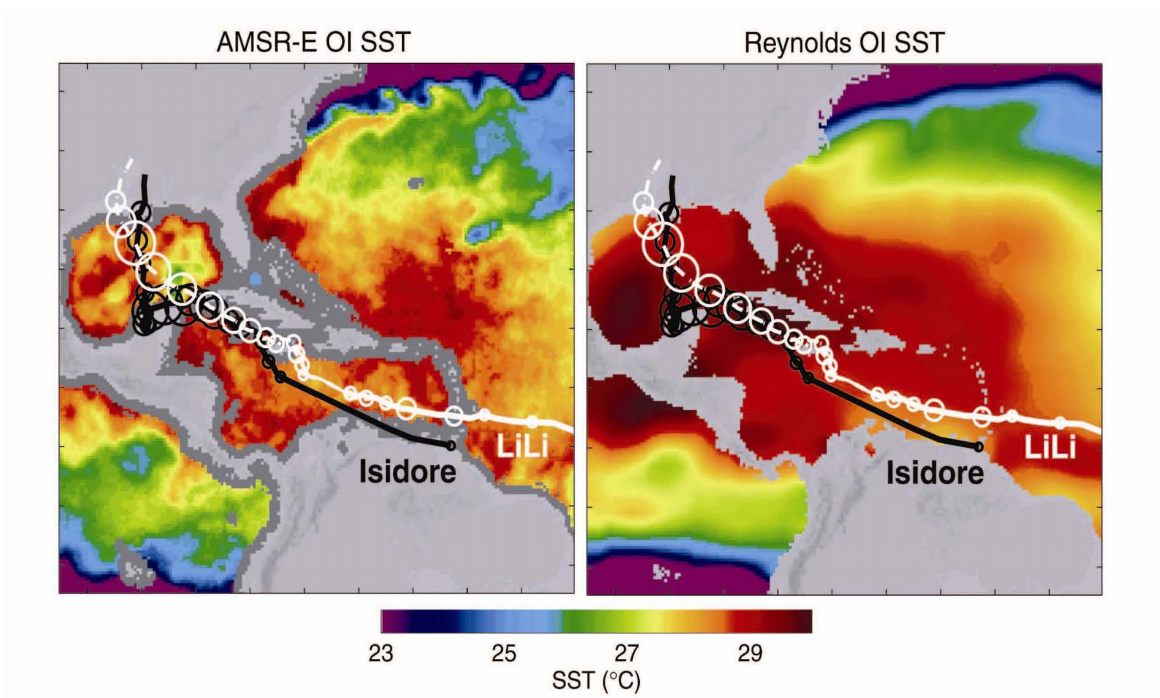

Figure 7. Daily, 25 km, MW SST and weekly, 100 km, NOAA NCEP SSTs on 28 September 2002. The MW SSTs show considerably more variability than the smoothed NCEP SSTs. The gray areas adjacent to land in the top panel represent areas where MW SSTs are not retrieved due to side-lobe contamination. In this image, Hurricane Isidore had just passed over the northern Yucatan Peninsula and weakened. The strong winds generated a considerable cold wake seen in the MW SSTs. Hurricane Lili followed a similar track only a few days later. The NCEP SSTs do not show the cooling North of the Yucatan Peninsula seen in the MW SSTs. With Lili following closely, timely knowledge of the oceanic thermodynamic structure was needed for forecasts. In this case, the NCEP SSTs were unable to provide this information to the intensity models.